FN-143
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NOTES ON LINAC CONTROL SYSTEM

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1.0 General Requirements

The control system to be provided for the 10 MeV section in the Linac Research Building will require all of the basic capability of the system for the entire 200 MeV Linac. The extension to the final system should require only additional multiplex capability.

The basic tendency for an automatic computer based control system design is toward including all interlock, control and monitoring functions in such a way that the computer is a completely indispensable component of the system - so indispensable that it is difficult, if not even impossible, to run the system without it. It will be our goal to resist this tendency but to incorporate into the computer based system only those supervisory, monitor and control functions which most usefully exploit the unique characteristics of the system. The following objective will be sought in the design:

1. The computer will be exploited as far as possible in achieving fast data acquisition and display for diagnostics of linac behavior in periods of machine investigation.

2. It must be possible to "run" the entire linac without the computer if necessary, However, this objective does not imply that all controls or monitoring signals will be hard wired to one central control point.

3. Independent systems will be "self-protecting" as far as local interlocks are concerned.

4. The computer will not generally be used to close servo loops but it may be used to set reference levels for the individual loops if its computational ability is of advantage in determining new set points.

In the following sections it will be attempted to outline those functions which, as presently conceived, should be monitored routinely and those whose conditions need only to be accumulated at a local center and alarmed to the operator if a malfunction occurs. Also those areas where provision must be made for extensive diagnostics at various times using the computer system will be pointed out.

2.0 Preaccelerator Controls

The preaccelerator controls naturally assemble themselves into three categories which are distinguished by some of the general requirements for the controls in that category.

2.1 850 kV power supply controls

All of these variables are at ground potential and can be simply monitored values or they may be controlled (either by on-off of set point adjustment) by the control system. These items include the following:

2.1.1 Power supply D.C. output

This voltage is read directly by a compensated voltage divider of about 10^5 to 1 dividing ratio. It should also be independently read by a generating voltmeter or other electrostatic induction type device. This voltage is one of the most sensitive parameters of the entire linac system and it must read out to at least 1 part in 10^4 and must be stable to better than that tolerance both long and short term.

2.1.2 Bouncer output

Since the 850 kV power supply must deliver a pulsed current of many times its dc current rating, and still maintain the stability stated above during this current pulse, it is equipped with a fast feedback output voltage control device, called a bouncer, which automatically compensates for changes of power supply output during the pulse.

The bouncer output must be monitored and the operator notified if operation is abnormal.

2.1.3 Rectifier stack input voltage

A high frequency ($\approx$10 kc) oscillator supplies the input voltage for the 850 kV power supply. This voltage is proportional to the output voltage but it should be monitored as a check on output voltage and for detection of malfunction.

2.2 Ion source controls

All of the electronic variables for the ion source will be isolated in an electrode at the output voltage of the preaccelerator power supply. These variables are conventionally controlled by insulating shafts from ground. Motors at ground potential turn the shafts. Variacs or potentiometers which control the variables are geared to the high voltage end of the shafts.

Some of these variables are voltages which are supplied by power supplies whose dc ratings are considerably lower than the peak currents required, especially under unusual beam conditions. Therefore it is desirable to sample all voltages at a predetermined time (perhaps even more than once during the pulse) and multiplex readings back to ground through a telemetry system. These signals should also be available as telemetered video signals at ground.
It should be pointed out that Dr. Lloyd Lewis at Argonne has recently built a system to serve this purpose and similar equipment should be suitable for us.

Variables to be included are:

2.2.1 Isolated M-G set output voltage - 117 volts

2.2.2 Cathode heater current
2.2.3 Cathode heater voltage } dependent on choice of cathode

2.2.4 Intermediate anode - cathode voltage - 20 to 50 volts

2.2.5 Intermediate anode - cathode current - to 20 amps

2.2.6 Anode-cathode voltage - 40 to 100 volts

2.2.7 Anode-cathode current - to 100 amps

2.2.8 Source gas pressure - 200 to 1000 microns

2.2.9 Extractor voltage - to 100 kV divider ratio $\approx 10^4:1$

2.2.10 Extractor current - to 200 mA, turn ratio on torroid can be adjusted for suitable output voltage.

2.2.11 Other variable high voltages may appear in the electrode depending on the final design details of the accelerating column.

2.2.12 Ion source turn-on and off pulses as described in 4.7.3.

2.2.13 Magnet current $\approx$ 100 amps

2.2.14 Magnet voltage $\approx$ 10 volts.

2.3 Beam diagnostic equipment at the output of accelerating column.

It is imperative that these devices be monitored by and controlled by a computer based control system so that diagnostic programs can be run quickly and reliably. Dr. Curtis is working out the details of this system and more specific definitions can be determined from him.

However, the following items should be prepared for monitoring and control by the system at an early date. (These may be in addition to others that will be determined later by Dr. Curtis.)

2.3.1 Beam torroid

A large aperture torroid should be planned at the ground end of the column which will monitor the total charge accelerated by the preaccelerator, to 1 amp.

2.3.2 Defining slits - (same as 4.9.4)

Probably at least two sets will be required.

2.3.3 Proton percentage annalyzing magnet

(note: this will probably be removable and will not be present when operating into the linac or it may be a steering magnet. Another possibility is a crossed E & H field separator which would be a permanent installation.)

2.3.4 Fast emmittance measuring equipment. (see Dr. Curtis)

3.0 Buncher - Section Control

The buncher is an RF cavity which velocity modulates the protons in the drift space between the preaccelerator and the linac so that a larger percentage of the protons arrive in the accelerating RF phase of the first gap of the linac than would occur in the normal unmodulated preaccelerator beam pulse.

Quadrupoles are placed in the buncher section which transform the optical characteristics of the beam from the preaccelerator column to those characteristics required for acceleration in the linac. Also in this section are steering magnets, beam detectors, defining slits and other diagnostic devices designed to aid in measuring the characteristics of the beam at specific places along the beam trajectory.

Controls for these devices should be planned from the beginning to exploit the capability of a computer system to do quick, reliable measurements.

3.1 Buncher voltage

The phase and amplitude of the voltage in the buncher must be independently monitored and controlled. Phase detection is the same as discussed in 4.8 and amplitude detection is discussed in 4.6.1.

If a separate amplifier is used for the buncher, these variables can be servo controlled as in the cavity sections.

3.2 Quadrupole currents.

These quadrupoles could be dc or pulsed, no decision on this matter has been made as yet. The quadrupoles will probably be grouped as tripletts (i.e. one half length quad in + polarity followed by a full length quad in - polarity, followed by another + polarity half length quad.) On command the currents in all three quads may be changed as a group by the same current increments. It also must be possible to control the quads of the group independently.

3.3 Other control and monitoring requirements

3.3.1 Steering magnets

These magnets are used in conjunction with beam position detectors to place the centers of gravity of the beam on the axis and parallel to the axis. Monitoring and control of this type of system using a computer has been done by Allison, et al at Berkeley. (See Procedures of 1966 Linear Accelerator Conference, pages 34-47 and 483-490)

3.3.2 Beam detectors

Both torroids and Faraday cups will be used in this region. These are discussed in some detail in 4.9.1. The retractable Faraday cups are also used in the personnel safety system to positively prohibit entry of beam into the linac when all personnel safety requirements are not satisfied. These cups also allow operation of the pre-accelerator while personnel are in the tunnel or while the linac is off for any reason.

Other devices which should be monitored and controlled by the control system:

3.3.3 Slits - as in 4.9.4

3.3.4 Vacuum pressure - as in 4.3

3.3.5 Vacuum isolation valves - as in 4.4

3.3.6 Buncher temperature - as in 4.2

3.3.7 Misc. interlocks as needed for water flow, temperature, etc.

4.0 Items Common to All RF Sections of the Linac

4.1 AC line voltage

Provision should be made for monitoring the voltage of each phase of each power line unit substation on demand of the control system. Tolerances should be established for allowable variations and the system should inform the operator of trouble if the voltage deviates outside of these limits.

This information need only be presented on request of the operator or when trouble is present.

4.2 Temperature

The center frequency of the response curve for each cavity will be controlled by controlling the temperature of each tank independently. The temperature control will be within the range of $\pm$ 0.1^{o}F and each tank will be initially tuned to have the same center frequency at 75^{o} $\pm$ 5^{o}F.

Each cavity temperature will be monitored and deviations outside of prescribed limits will be alarmed through the control system.

The set point of the servo system for cavity temperature control can be varied through the automatic control system by information from the phase detectors (4.7.2 g) to keep the cavity fast phase control system within its range.

4.3 Vacuum pressures

All sections of the machine will be maintained at vacuum pressures of 1×10^{-6} mm of Hg or less. This pressure can be monitored by monitoring ion gauge readings or ion pump currents. Since all parts of the system will be ion pumped it seems more reasonable to monitor the ion pump currents and not provide ion gauges as a routine requirement.

Ion pump current varies directly with pressure, hence it is a logarithmic variable but it should not be necessary to monitor this variable over more than 3 decades. Accuracy of better than $\pm$ 20% is not needed.

Upper limits for each section pressure will be determined which will be used as alarms and to initiate the closing of isolation valves. It will also inhibit the RF pulsing to a section whose pressure has risen beyond the limit and turn the beam off.

The vacuum signals will not initiate any other automatic operation. (i.e. no start-up sequences will be used.)

4.4 Vacuum isolation valves

A remote actuated isolation valve will be included between tank sections (except between tanks 1 and 2). These valves allow the vacuum systems of each tank to be independent when the beam is not in operation.

Condition (i.e. open-close) of these valves will be positively monitored by directly actuated limit switches. The beam must not be allowed to hit the valves when they are closed, therefore:

a.) the beam must be inhibited under conditions where any valve upstream from the point at which the beam will be stopped by a Faraday cup is open.

b.) valves will be closed by the pressure in a section rising above a prescribed limit.

c.) the control system will display the conditions of isolation valves which prohibit beam operation.

4.5 Faraday cups

Remotely actuated Faraday cups will be provided between tank sections which will allow the beam to be intercepted at that point.

These will be controlled and monitored as are the isolation valves in section 4.4.

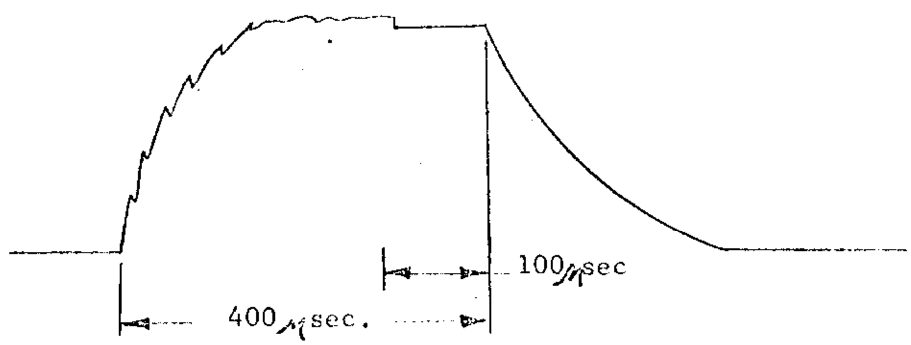
4.6 RF fields in the cavity

RF fields are measured in each cavity section using RF magnetic field pickup probe. Probes will be provided at the axial position of the center of each accelerating gap but all of these are required only for initial cavity tuneup and diagnostics.

4.6.1 Routine operation

The rectified RF output of 3 loops in each cavity, one at the center and one toward each end, should be available for monitoring. Each loop must be calibrated and the ratio of the three known for the desired tilt.

These signals look as follows:



These pulses must be monitored during the beam pulse to 0.02% or better since these are among the most sensitive parameters of the entire linac.

Since each loop output will be followed by a follow and hold amplifier the gains can be adjusted so that the pulse height represents a high enough voltage as to be well out of the noise at operating levels. Argonne uses voltages about 2.5 volts for normal operating levels, which would seems to be a reasonable value.

4.6.2 Initial tune-up and diagnostics

Each of the probes in a tank section should be monitored during tank flattening and initial tune up procedures. Enough test probes and associated electronics should be provided to instrument one entire tank section at one time but they can be moved from one section to another as needed during the installation and start up phases.

Lloyd Lewis at Argonne has described the use of these probes for cavity field measurements in the "Proceedings of the Sixth International Conference on High Energy Accelerators, 1967", pages 261-269. This is the general direction in which we should go for instrumenting the loops.

In addition there will be low level perturbation measurements made on each cavity using the frequency changes caused by a perturbing ball being pulled through each gap to measure the electric fields in each gap of the section.Curt Owen has described these techniques in the "Proceedings of the Los Alamos Linac Conference, 1966" pages 140 to 145. Planning to instrument this activity should follow these guidelines.

4.7 Cavity RF systems

Each cavity is driven by a separate RF amplifier. Although we are in the process of reconsidering the level of the drive power to each cavity amplifier we will consider here only the most complex case, where a complete amplifier chain is provided for each cavity.

A general block diagram of each system is shown in Fig. 4.7.1

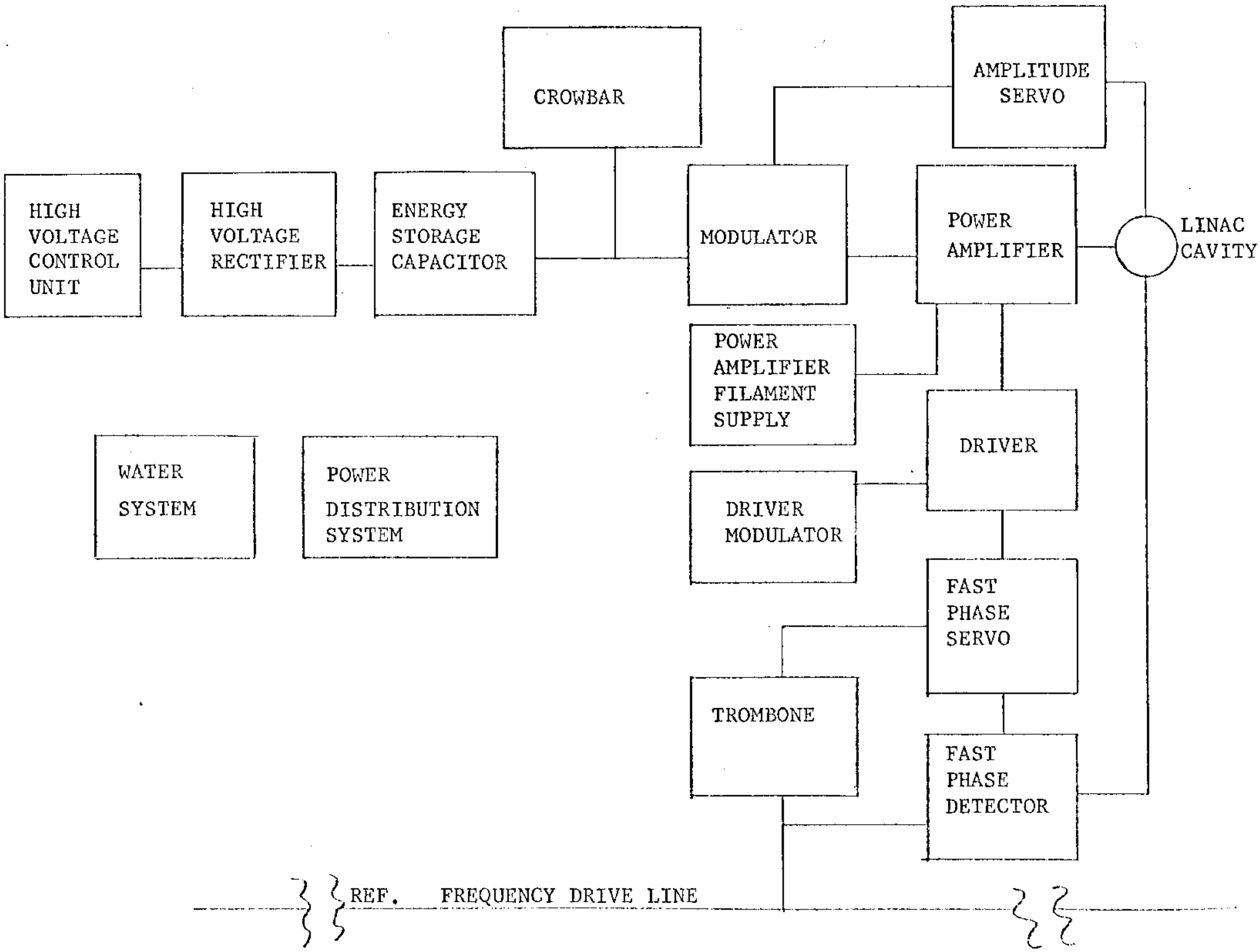


FIG. 4.7.1

BLOCK DIAGRAM FOR A SINGLE CAVITY RF SYSTEM

The following information should be monitored and displayed on request of the operator or whenever monitored values exceed prescribed limits.

4.7.1 Status

Summary of interlock conditions

Summary of on-off status

Malfunction which turns "off" some unit

Crowbar operation

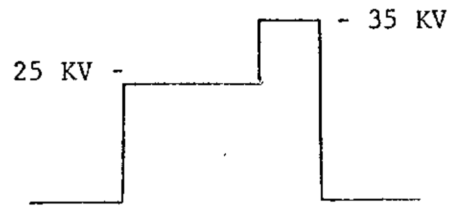
4.7.2 Monitoring operating conditions

A. High voltage on capacitor bank using compensated voltage divider output. Nominal voltage operation -50 kV, monitored at 10,000 to 1 divider ratio.

B. Current from high voltage rectifier for shunt in ground side of rectifier.

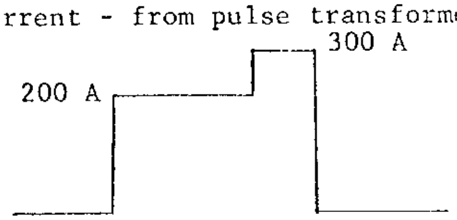
C. Modulator pulse output to P.A.

1. voltage - from compensated divider



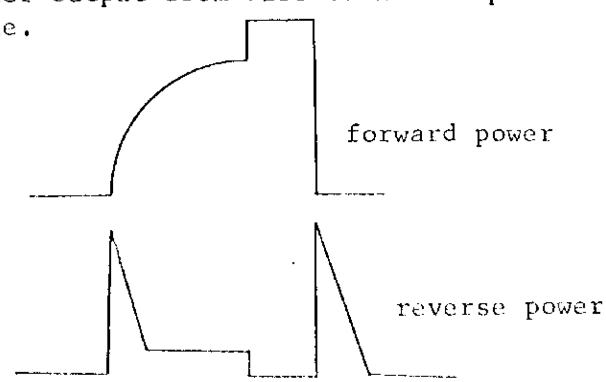
divider ratio $10^4:1$

2. current - from pulse transformer



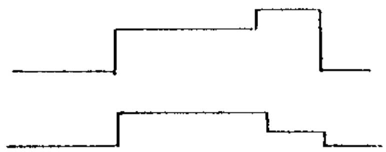
1V = 100 amps

D. Power amplifier output from directional coupler in output line.



Signal levels can be adjusted to suit

E. PA input power from directional coupler in the line from driver.


forward power
reverse power

Voltages can be adjusted as desired

F. Phase shifter (trombone) position. A drive motor with limit switches and a geared position potentiometer will give a voltage which is proportional to phase shifter position.

G. Fast phase servo operation. An error signal is developed from each fast phase detector which develops a voltage which is related to the phase shift of the varicaps in the fast phase shifter for fast phase correction. This error signal should be monitored. If it goes beyond preset limits it can be used to correct phase shifter position. (F. above) to bring back to original set condition.

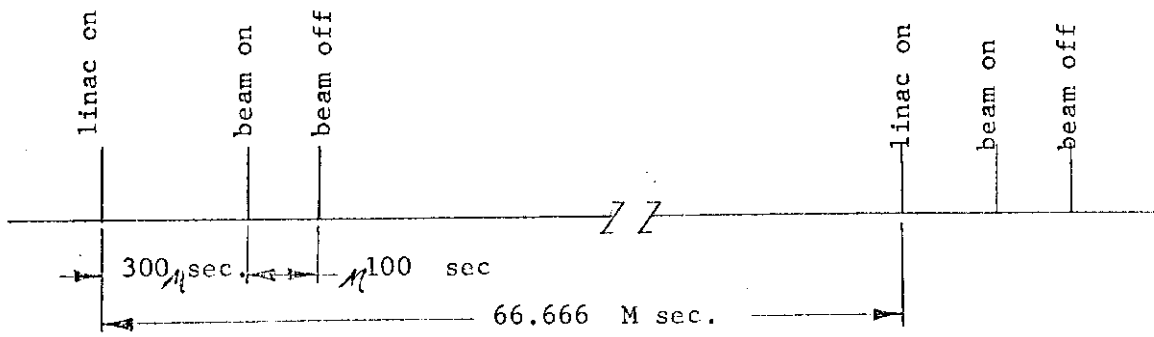
H. Amplitude servo. Monitor the reference level and error signals of the amplitude servo.

4.7.3 Control functions

Clearly a computer based system can be expanded to include all start-up and shut-down sequence. However, this seems at present to be more elaborate than needed and therefore not presently justified. However some control should be available from the beginning.

A. Injector timing. The precise timing of the linac will be determined from the field of the booster ring magnet. However, the control system should give "linac turn on" pulse to each RF system for independent operation 15 times per second.

Each linac turn-on pulse shall be followed by a "beam on" pulse to the ion source after a preset delay. This delay will vary from 200 to 300μ seconds. A "beam off" pulse will follow after an additional delay of from 25 to 100μ seconds. The beam off signal can also be used to turn off the linac RF if desired.



B. Appropriate logic hard ware should be incorporated with these pulses for permissive interlocks in case appropriate conditions for beam acceleration in the linac are not achieved.

4.8 Relative phase to the preceeding tank

The phase of a cavity relative to the preceeding cavity must be continuously monitored. This is done by comparing two equal signals from each cavity in a rat race phase bridge. A calibrated signal is derived from the bridge which is proportional to the phase difference between the two RF signals.

4.9 Beam measurements between cavities

4.9.1 Beam intensity

This will usually be monitored by torroid coil on a ferrite ring through which the beam passes in the intertank space.

Lee Parslow at Argonne has developed the associated circuitry, complete with follow and hold amplifiers and calibrate pulses which follow the beam pulse. These circuits are directly transferrable to the NAL system.

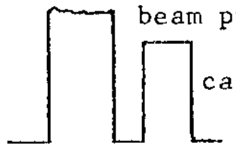


Fig. 4.9.1 Torroid Output with Calibrate Pulse

Also provided will be retractable beam stops, or Faraday cups, between tanks which allow direct measurement of the beam by measuring the voltage developed across a resistor which connects the cup to ground. It is generally good practice to use a terminating resistor which matches the coax cable being used so that beam pulse reproduction is good. Thus the usual sensitivity is .050 Volts/mA in a 50 Ω system.

4.9.2 Beam position

The axial position of the center of gravity of the beam can be obtained from sets of induction electrodes or pick-up loops which develop difference signals depending on their relative position to the beam.

These devices have been developed at ANL, LRL, and Brookhaven and can be essentially copied.

4.9.3 Beam profile detection.

Dr. Michel Shea Argonne is working on a non destructive system for displaying the beam density distribution along the linac. The inter-tank space should contain such devices if the sensitivity proves to be sufficiently good at our operating pressures to use them. These also can be used for beam position detection, 4.9.2 above.

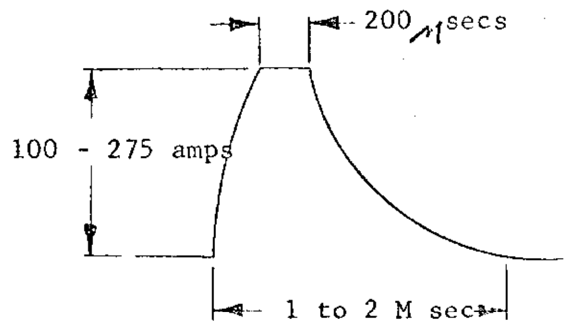
4.9.4 Defining slits

If the profile detectors (4.9.3 above) work there is perhaps no need for slits in the space between tanks. However, it seems wise to plan for them at this time. Slits of variable width (.010" to .250") for both horizontal defining and vertical defining shall be provided at each tank interval as well as at selected points between the preaccelerator column and the first tank and at selected positions along the beam line at full energy.

Position of the center of the slit should be read out to $\pm$ .002" into the computer and position control must be within the computer.

4.10 Drift tube quadrupole currents.

Each drift tube of the linac will contain a quadrupole magnet which will be pulsed in pairs. The currents to each pair must be monitored and alarmed if the peak current go outside of about $\pm$ 0.5% limits. The wave form of the current will be similar to the following sketch:



The current detector can be a ferrite core torroid and the turns on the core can be adjusted for any reasonable voltage output.

Interlocking the water flow to the quadrupole and drift tube cooling circuits can be accomplished either by flow switches or detectors which sense the temperature rise of the conductors to the quadrupoles. In the latter case a computer based control system can be easily used to protect the quadrupoles.

4.11 Other variables

Each cavity system contains many variables not yet mentioned which may need to be incorporated into the system but which for the present will only be listed.

A. Power amplifier output loading (tap position)

B. Power amplifier output tuning (tuner position)

C. Power amplifier output line matching (stub position)

D. Power amplifier input tuning

E. Power amplifier input loading

F. Coupling loop penetration (2 each)

G. Coupling loop matching stub position (2 double stubs/tank)

H. Driver output tuning

I. Driver input tuning

J. Power amplifier filament current

K. Power amplifier filament voltage

L. Power amplifier output cavity pressure

M. Low pressure water conductivity

N. Quadrupole pulser charging voltages

O. Quadrupole pulser timing

5.0 Debuncher Section

Bending and focussing elements are placed in the drift section between the end of the last linac section and the booster ring for control of the beam characteristics. This section also contains sensors for monitoring these characteristics as well as the final cavity section (called the debuncher) which is used to minimize the energy spread in the 200 MeV beam.

All devices in this section are similar (so far as control requirements are concerned) to those items in the Buncher section. So for the purpose of these notes the items will only be listed.

5.1 Debuncher phase and amplitude - will probably use a separate drive amplifier - see 3.1

5.2 Quad currents - probably doublets rather than triplets - see 3.2

5.3 Steering magnets - see 3.3.1

5.4 Beam detectors - see 3.3.2

5.5 Beam profile detectors - see 4.9.3

5.6 Slits - see 4.9.4

5.7 Vacuum pressure - see 4.3

5.8 Vacuum isolation valves - see 4.4

5.9 Debuncher temperature - see 4.2

5.10 Misc. interlocks

6.0 Building Facilities and Utilities

Quite obviously numerous building facilities can be incorporated into the control system if desired. Each of these should be independently reviewed and the merits of using the computer based systems evaluated for that particular use. The following is a partial list of such possibilities in a supervisory system sense.

6.1 Fire alarms

6.2 Water pressures and temperatures

6.2.1 Water pump status

6.3 Air conditioning system operation

6.4 Status of substation main breakers

6.5 N_2 pressure in building dry gas distribution system

7.0 Beam Diagnostics

For the purpose of illustrating the use of the control system for beam diagnostic purposes let us consider some specific, simple experiments and how the system can be used to accomplish them.

7.1 Measure the energy profile at 200 MeV at specified conditions. A number of conditions would be determined for this measurement by the physical layout of equipment used but for this purpose it will be assumed that these conditions have been taken into consideration before hand. These things include position of slits, positions of the analyzing magnet and quadrupole currents for as parallel as possible a beam into the analyzing magnet. See Fig. 7.1.1.

On command to make the measurement the control system will:

A. Center two vertical slits (A & B) in the beam ahead of the analyzing magnet.

B. Raise the current in the analyzing magnet until beam is just detected through a fixed slit, following the analyzing magnet.

C. Form coordinates on a display scope of intensity through the analyzing slit (slit C) versus energy of the beam (as determined from current in the magnet.)

D. Step the analyzing magnet in $\frac{\Delta E}{E}$ of .01% steps on each linac pulse through to the opposite side of the energy peak and beyond by 0.5%.
   1. Analyze and plot data on the scope for each point and check operating parameters for each pulse. See Fig. 7.1.2

E. Return in 0.01% increments to $\frac{\Delta E}{E}$ of 0.5% below the energy peak and repeat the curve.

F. If requested by the operator, print the curve from the display scope on an electrostatic printer or xy plotter.

This measurement can now be quickly repeated for other settings of a variable, say RF level in one cavity, while maintaining all other variables constant. Thus a family of curves can be quickly achieved of energy profiles and how they are changed by variations of a single variable.

In the case of the 200 MeV linac where achromatic bending magnets are used, the beam density profile detectors (see section 4.9.3) can be placed at the position of maximum energy dispersion and the energy distribution can be continuously monitored, non distructively, on each pulse. In addition to this, any variations of energy distribution during the pulse can be observed directly from the profile detectors.

7.2 Tuning of input parameters.

A number of the input parameters of the linac, say for instance the buncher section quadrupoles, are optimized by tuning across their operating range and observing the intensity of the accelerated beam.

7.2.1 On demand the control system displays coordinates on the display scope of the beam intensity at the end of tank number 1(I_1) versus current in the first quad of second triplet (here called Q201).

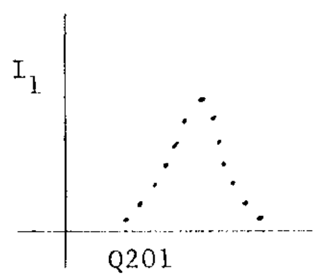


Fig. 7.2.1

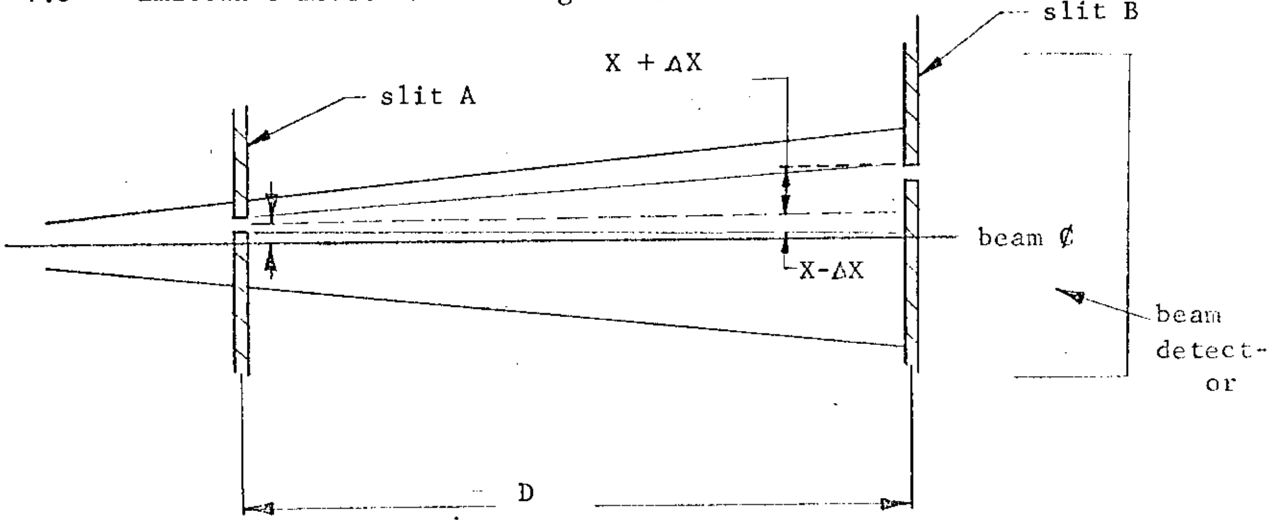
7.2.2 Control system varies Q201 by .1% intervals per pulse over range and plots I_1 vs. Q201 on display scope.

7.2.3 Set Q201 at optimum value, print display on electrostatic printer if desired.

7.2.4 Change to Q202 (second quad of second triplet) and vary and plot as in 7.2.2. Set at max I_1.

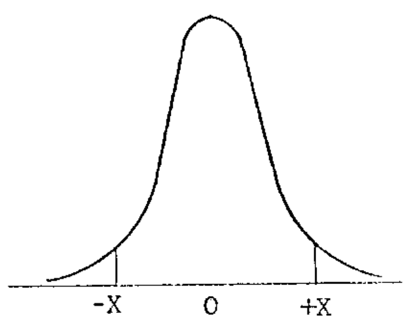
7.2.5 Change to Q203 and repeat. Set at max I_1.

7.3 Emittance measurement using two slits.



A. On command to make the emittance measurement, slit A moves into the beam. The x profile of the beam is plotted at the Beam detector and is displayed on the display scope.

B. The area under the curve is integrated and the $+X_o$ and $-X_o$ positions, which exclude the outer 10% of the beam, are determined.



C. Slit A is set at $-X_o$ position.

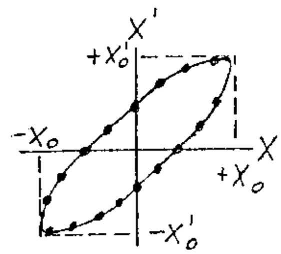
D. Slit B is traversed through the beam and the profile through both slits is plotted on the display scope. Coordinates of the ends of this profile determine the values of $X'_o = \frac{k}{d}$ at the $-X_o$ position.

E. Advance slit A to a position 0.1" closer to x=o.

F. Repeat step E, determining new X' values.

G. Repeat step E and F repeatedly until the $+X_o$ value is reached.

H. Plot all values of X, X'



A finer examination shows that slit width corrections must be made etc. but this general proceedure can be followed to simply measure the emittance of the beam. It can be expanded to use two sets of orthoginal slits but this only slightly complicates matters.

It is hoped that non destructive measurements of emmittance will be possible by using several sets of profile detectors as described in 4.9.3.

These examples only illustrate three possible uses of this system for beam diagnostics. Detailed plans for such measurements need not be made for sometime, but the ability to make the measurements must be recognized in making decisions on hardware today.

8.0 Computer Equipment Requirements

As described in these notes the computer is used principally to address various monitoring channels, process the data from these channels and prepare display from memory which are needed by the machine investigator. In order to accomplish this the computer needs the following minimum characteristics.

data word length - 16 bits

memory - 12K (expandable to 32K)

memory cycle time - 1.0 μsecond or less

multiply/divide time - 20μsecond or less
priority interrupt system
real time monitor
memory protection
paper tape reader and punch
typewriter

These and other more detailed requirements are specified in the system specification.

In addition other peripheral equipment will be required for the complete system. These units will include:

A. A card reader
B. A CRT display unit
C. A non-impact line printer
D. An x-y plotter
E. A mass storage device - disc or drum.

When considering the detail requirements of these individual units, and recognizing the time in the schedule when they will be needed, it is expected that these units will not be specified until late summer or fall of 1968 in order to benefit from experience elsewhere and expected improvements in available equipment.